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Optimising power transmission options for marine energy converter farms

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ABSTRACT

This paper introduces a techno-economic analysis framework to assess different transmission options for marine energy converter (MEC) farms. On the technical front, the feasibility of the transmission options considering supply quality constraints and the optimal sizing of reactive power compensation to allow maximum real power transfer capability in the subsea transmission cable have been considered. The economic viability of different transmission options are measured based on component costs and the costs associated with the transmission losses. A case study has been presented in the paper, which demonstrates the application of this techno-economic analysis framework on a range of MEC farm sizes and distances from the shore. The results characterise the performance of different transmission system options with respect to three key design parameters – distance to shore, array power and transmission voltage – and provide guidance for system design.

1. Introduction

As marine energy converter (MEC) deployment moves from single device installations to arrays and farms of devices, a concept engineering study of the electrical infrastructure is required to inform the connection of these commercial scale farms to the electricity network. Although the marine energy sector can learn from experience in the offshore wind sector, e.g. [1–3], there are a number of engineering challenges which are unique to the marine energy sector. The fact that there are potentially more subsea components in areas with stronger wave and tidal current conditions creates new design challenges for the operation and installation of electrical networks and components.

The harsher operating conditions in the marine renewable energy (MRE) environment may require the use of specialised components, which are generally more expensive than commercially available products. This can result in a higher levilised cost of energy (LCOE) – which defines the power cost per unit to break even over the project lifetime – than competing offshore generation technologies. In order to gain a market share, the LCOE of MEC arrays has to be comparable. Without subsidy, there are two general ways to achieve this: by reducing component cost or by maximising the use of existing assets. Reducing component cost will require an increase in production volume and will only happen when the industry reaches

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maturity. However, by detailed cost-benefit analysis, electrical networks can be designed to ensure maximum possible return for the available resources and network capacity.

In this paper, a techno-economic analysis framework for allowing maximum real power transfer across the transmission network is described. This is illustrated by assessing the impact of three of the most important array design parameters – the installed capacity, the export cable length and the transmission voltage – on the cost and performance of the transmission system. The boundaries of these parameters are defined with respect to the current needs of the industry, and are representative of pre-commercial and full commercial deployment. They are set to installed capacity of less than or equal to 100 MW and an export cable length of less than or equal to 50 km, respectively [4].

In this operating region, ac transmission is still the most economical solution (dc transmission may become a better solution for distances greater than 50 km and for farm sizes greater than 500 MW [5–7]). With ac transmission, the capacitance of the cables causes a charging current to flow through it. This limits the real power transfer back to shore if the transmission system is not properly designed. The fact that the cost of the export cable is high, and that it can constrain the output of the array, makes it particularly interesting for cost-benefit analysis.

The transfer capability of the ac transmission can be improved using reactive power compensation and a detailed study of the sizing of onshore and offshore reactive power compensation to utilise the transmission capacity of the export cable is presented. A case study investigates the impact of reactive power compensation on the cost and efficiency of the MEC array transmission system, highlighting the importance of the design of the transmission network to the array performance. Power losses within the intra-array network are generally small in comparison with the transmission network losses and the design of the intra-array network is a different process altogether; accordingly, the efficiency of the intra-array network is not considered in the analysis. The results presented here are part of ongoing research and will serve to highlight the sensitivity of the overall system to alternative designs, and will help to determine the prevailing parameters for optimal design of offshore networks.

The paper is structured as follows. Section 2 introduces the main subsystems present within an offshore MEC farm. The techno-economic analysis framework is defined in Section 3. Both the technical and economic aspects considered in this work are described in more detail in Sections 4 and 5, respectively. A case study is presented in Section 6. The conclusions and areas of further work are discussed in Section 7.

2. Design of marine energy converter farms

The electrical system of a MEC farm follows a hierarchical structure from production to grid connection. A generic offshore network architecture is shown in Fig. 1 which clearly identifies the subsystems within. Note that the terms MEC array and MEC farm have been used interchangeably in this paper, and have not been selected based on the rating of the development and/or the number of devices within it.

The design of the MEC farm layout depends on a multitude of factors, ranging from the site characteristics and the level of performance required from the system to the available capital cost. Some of the most important decisions which must be taken during the design can be defined as follows:

- The transmission system between the collection point and the onshore network.
- The number and type of offshore collection points.
- The intra-array network layout.

The network design will typically start with the selection of the export cable of the transmission system. Once this has been defined, the need for a collection point is then assessed, which will be performed in conjunction with decisions on the layout of and control within the intra-array network. This section presents an overview of the options that are currently

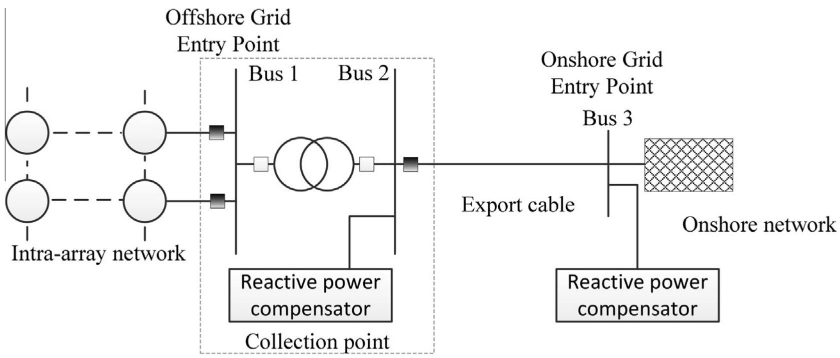

Fig. 1. Simplified generic offshore electrical network for MEC arrays.

available to the network designer, focussing on the transmission system and the collection point as these are most pertinent to the analysis presented in this paper. A brief discussion of the intra-array network is included for completeness. The interested reader can find a comprehensive overview of the whole system, and the components within, presented in Ref. [8].

2.1. Transmission system

As previously discussed, the distances (less than 50 km) and transferred power (less than 100 MW) currently required by the MRE sector can be served using ac transmission systems. Alternative dc solutions are being considered as a way to improve the commercial viability, e.g. [5,7], but are still in the pre-commercial/R&D phase. The main disadvantage of ac transmission systems is the requirement of reactive power compensation when the transmission distance becomes long and the size of the farm increases. The impact of this is discussed in detail in later sections of this paper, where it is shown that compensation may be required both onshore and offshore. The offshore compensation will be housed within the collection point discussed in the following section.

2.2. Collection point

Due to the high cost of the export cable, it is expected that commercial scale arrays will collect the power generated by the individual MECs at offshore collection points in order to reduce the number of transmission cables required. Collection points can be classified into two general categories:

- *Passive hub:* Which collects and exports power at the intra-array voltage. This may or may not include switchgear.
- *Offshore substation:* Which includes a step-up transformer, its associated switchgear, and any reactive power compensation.

It is possible to have subsea and surface piercing variants of both; however, a surface piercing passive hub is unlikely to be found in practice. Floating hubs are also possible but are still in the early stages of development.

At the current time, there is no technological convergence on the design of collection points for MEC farms. However, it may be assumed that they will consist of a single or double busbar configuration with switchgear, power conditioning equipment and step-up transformers included dependent on design requirements. For the purpose of the analysis in this paper, switchgear and busbar configurations are assumed to be similar to those used in offshore wind farm collection points.

2.2.1. Transformers

Within MEC farms, transformers may be present within each MEC device and may also be required in offshore substations. For use offshore, the cooling arrangements within transformers are different to those used onshore. For indoor use dry, air-cooled type transformers are preferred [9]. For outdoor use, liquid-cooled transformers need to be hermetically sealed and the cooling medium should be non-toxic [9].

2.2.2. Power conditioning equipment

Power conditioning equipment covers all filter types required to ensure grid compliance and also reactive power compensation to ensure optimal utilisation of transmission/export capabilities. This can be divided into: harmonic filters, reactors, capacitor banks and flexible AC transmission systems (FACTS). As this research is concerned only with steady-state power flows, only the selection of reactive compensation is considered in detail in this paper.

2.3. Intra-array network layout

An array of MECs consists of multiple converters linked by subsea cables, delivering electricity to the onshore network. There are a number of intra-array network layout options available for MEC farms, with some examples in Fig. 2. Note: the busbar shown in Fig. 2 corresponds to the offshore grid entry point (GEP, bus 1) in Fig. 1.

All of the layout options are variants of the radial layout, with different levels of redundancy. The number of devices per radial string is a technical constraint which is decided based on the rated capacity of the device, the spacing between two neighbouring devices and the rating of the intra-array cable [10]. The layout is chosen as a trade-off between power losses in the network, its robustness and the cost of the farm. However, the resource characteristics and the sea bed conditions of the site are also crucial factors to be considered before the intra-array electrical network is designed.

Detailed design and optimisation of intra-array networks is beyond the scope of this paper as the focus is primarily on the transmission network to shore. In this paper the power losses within the intra-array network are not included in the analysis that follows. A comparison of the performance of different intra-array networks is available in Ref. [11].

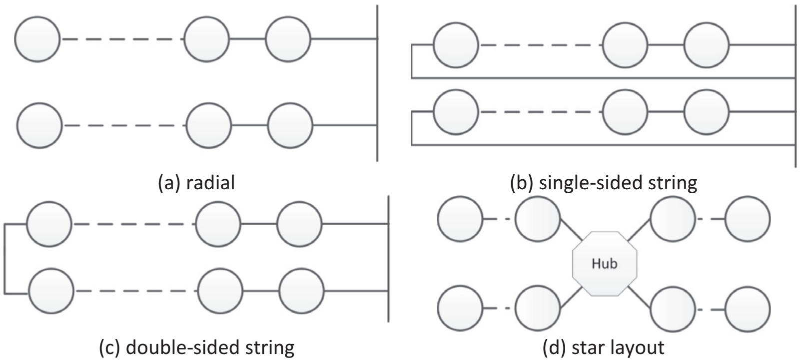

Fig. 2. Intra-array network configurations.

3. Techno-economic analysis framework

Techno-economic analysis is a widely implemented approach for comparing systems when more than one solution is possible. The performance of each solution is effectively normalised against the cost until an optimum value is reached.

There are two cost categories that should be included when evaluating the transmission system. The first one is the actual cost of components of the transmission system. This cost is a function of the network capacity and redundancy and increases with network capacity and/or redundancy. The second is the cost associated with generated energy lost in the form of transmission power losses. These losses generally reduce with an increase in network capacity. The objective of the techno-economic analysis is, thus, to identify the transmission system configuration corresponding to the lowest total cost point of this trade-off.

The techno-economic framework is developed around a MATLAB power flow solver [12] to analyse the network performance: ensuring technical feasibility and accurate assessment of network losses. The process for a given export voltage rating can be described as follows:

1. Define array characteristics: rated power and intra-array operating voltage.
2. Calculate the power output of the MEC farm for each identified sea state.
3. Assess technical feasibility: steady-state voltage variations and reactive power compensation. Proceed if the solution satisfies grid code requirements.
4. Run the power flow for each identified MEC operating condition.
5. Multiply the transmission loss for each sea state with the frequency of occurrence of that sea state to calculate the energy loss in Watt-hours.
6. Sum the transmission loss over the entire range of sea states to obtain the total energy loss.

Further details on the technical feasibility and the cost modelling are included in subsequent sections.

4. Technical feasibility

Commercial size arrays must achieve Grid Code compliance. For the steady-state power flow analysis considered in this research, the MATLAB power flow solver is used to assess the steady-state voltage variations and reactive power support. All discussions here refer to the UK Grid Code requirements [13].

4.1. Voltage regulations

In the offshore network, the voltage variation from nominal is determined by the number and rated power of devices connected to the radial and the impedance of the cables. The offshore voltage regulation requirements are assumed to be identical to the onshore requirements. For the medium voltage levels considered in this analysis, the voltage regulation requirements stipulate a maximum steady-state operating range of 0.9–1.1 pu [14].

4.2. Reactive power compensation

In offshore MEC farms with ac transmission systems, the capacitance of the cable causes a charging current to flow through it. The thermal characteristics of the cable limits the continuous current that it can safely carry. Therefore, if the charging current is high the real power that the cable can transmit is constrained. The distance over which real power can be efficiently transmitted by an ac cable is limited due to this characteristic.

There are two sources of charging current in MEC farms: the intra-array network cables and the transmission link to shore. Adequate reactive power compensation, both onshore and offshore, is required to fully utilise the real power carrying capacity of subsea cables. This is particularly important considering the high procurement and installation costs of subsea cables. This section presents a methodology to determine the optimal size of reactive power compensation to maximise the capacity of the transmission link. The power factor at the offshore grid entry point (bus 1 in Fig. 1) is fixed at 1 (unity power factor – UPF) to meet the UK Grid Code requirements [13].

4.2.1. Offshore reactive power compensation

The amount of offshore reactive power compensation is determined using an iterative method shown in Fig. 3. This is based on a procedure designed for offshore wind farms in Ref. [1]. The reactive power compensation Q_{comp} at the offshore substation is selected to allow the maximum possible real power transfer P_{gen} for the smallest offshore compensation and a given cable rating MVA_{rating} and length. As a severe voltage rise at bus 2 (Fig. 1) may be observed for some of the lower rated cables, the reactive power compensation is also sized to ensure that the bus 2 voltage $V_{bus,2}$ remains within 0.9–1.1 pu (UK limits) [14], denoted by $V_{limit,lower}$ and $V_{limit,upper}$ in Fig. 3. To meet the supply quality requirements, there may be a need to constrain generation due to capacity limits imposed by the reactive power transmitted through the transmission cable, as indicated in Fig. 3.

In the iterative procedure, P_{step} is a predefined step size setting the active power outputs at which the array is assessed, Q_{step} defines a discrete step for the sizing of the reactive power compensation unit and Q_{max} is a user defined maximum size

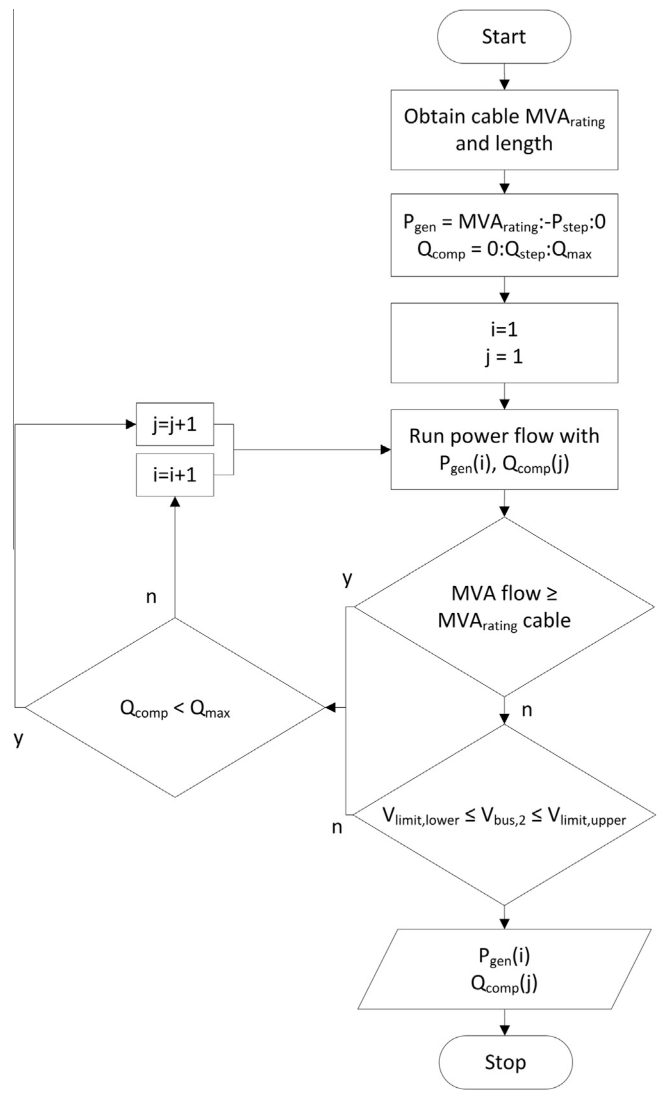

Fig. 3. Flowchart for determining the optimal value of the offshore reactive power compensation.

for the hypothetical reactive power compensation unit. The output of this procedure specifies the optimal amounts of reactive power compensation, required to meet supply quality constraints and to allow maximum real power transfer through the transmission link, for all the MEC farm power generation levels. The size of the reactive power compensator required for the MEC farm is then chosen to be the maximum of the optimal amounts of reactive power compensation selected for the different power levels assessed.

4.2.2. Onshore reactive compensation

The onshore compensation required is calculated to maintain the voltage at the onshore GEP at 1 pu. Although the voltage at the onshore GEP (bus 3 in Fig. 1) is defined through an agreement between the network operator and the generator operator [13], 1 pu is a reasonable assumption [1]. The offshore compensation aims to maximise the real power capacity of the cable (by reducing charging current) and to ensure that the offshore substation voltage lies within statutory limits. The onshore compensation does not affect the charging current that the cable carries and, thus, can be treated separately.

To size the onshore compensator appropriately, the reactive power exchanged at bus 3 (Fig. 1) under the maximum and minimum power generation scenarios is analysed. Depending on the size of the MEC farm and the length of the transmission link the reactive power compensator may need to either absorb or generate reactive power. The onshore compensator is sized to the largest value of reactive power exchanged at the onshore GEP (bus 3 in Fig. 1) when comparing the maximum and minimum generation scenarios.

5. Cost factors

As previously discussed, the cost factors to be considered are the capital cost of the transmission system and the cost associated with the losses. The cost of the subsea connectors and the MECs have not been included in the framework as their unit price and the number of units is fixed for all transmission options considered.

5.1. Transmission system investment cost

The cost of the offshore transmission system includes the cost of the submarine cable and the offshore platform (including the electrical equipment, e.g. transformers, switchgear, and reactive power compensation, on it). As there are no commercial MEC farms in operation today, the cost models of the power transmission equipment from the offshore wind industry have been used here. This is justified as the power transmission equipment within both these industries is identical. The cost models for transformers, subsea cables, offshore platforms and switchgear have been obtained from Refs. [1,3,4,15]. As part of ongoing research in Ref. [4], an MRE component database with indicative cost functions will be made publically available at a later date.

5.2. Transmission system losses cost

Once the total energy loss in the transmission system is identified, the cost associated with it can be calculated. An estimate of the price of the generated energy is required for this. In the UK, for example, under the Contracts for Difference regime, the strike price per MWh of wave or tidal generation can be used [16]. This price multiplied by the total energy loss gives the cost associated with the energy loss.

6. Techno-economic analysis framework: case study

In this section, the techno-economic analysis framework is applied to a wave energy case study. This quantifies both cost components (either directly as a cost or as a measure of the cost involved) for a range of different farm sizes and distances from the shore and demonstrates the impact of these parameters on system efficiency, system cost and sizing of reactive power compensation.

The technical assessment of the transmission system options is focused on the evaluation of transmission power losses. Transmission losses for a range of farm sizes (0.75–99.75 MW) and distances from the shore (10–50 km) were calculated. Appropriately sized cables, substation transformers and onshore and offshore reactive power compensators were selected for each case. The electrical characteristics of subsea cables were obtained from Refs. [17–19]. The impedances and the X/R ratios of the transformers were obtained from Refs. [20] and [21]. The electrical parameters of the cables and transformers used are listed in the Appendix.

Some assumptions about the transmission system design have been made in this study. These assumptions are:

- AC transmission with a single three-core XLPE subsea cable has been used.
- The MECs generate at 0.69 kV.
- Each MEC has an on-board 0.69:6.6 kV transformer.
- The intra-array network operates at 6.6 kV.
- All solutions have an offshore platform.

– One transformer per substation/platform.
– Transmission at 11, 33 or 132 kV.
– Switchgear for the substation transformer primary (6.6 kV) and secondary (11/33/132 kV) voltage levels.

6.1. Resource data and device power characteristic

For the analysis, wave data from the Belmullet wave energy test site, located off the west coast of Ireland was used [22]. Fig. 4 shows the scatter plot of the sea states at the site over a year. Note that the mean wave periods and significant wave heights over 60-minute durations are shown in the scatter plot.

The MEC farm used in the study is a wave energy converter farm of the Pelamis P1 device, each rated at 750 kW. Fig. 5 shows the power matrix of the device. The resulting power output histogram for the site and technology combination is presented in Fig. 6. High power output is observed for the site, representing favourable resource conditions and high performance of the selected device.

Significant wave height (m)										
0.5	17	39	13	0	0	0	4	0	0	0
1	148	312	93	32	13	0	1	0	0	0
1.5	75	560	372	187	64	11	2	0	0	0
2	6	427	623	321	172	47	8	0	0	0
2.5	0	99	508	363	182	67	10	0	0	0
3	0	10	248	394	193	83	18	2	0	0
3.5	0	0	86	436	244	74	15	7	1	1
4	0	0	14	213	246	97	23	7	8	0
4.5	0	0	0	83	218	124	22	4	3	2
5	0	0	0	17	175	118	26	3	5	3
5.5	0	0	0	0	88	122	36	2	1	0
6	0	0	0	0	30	86	37	3	3	0
6.5	0	0	0	0	0	45	32	4	4	1
7	0	0	0	0	0	24	48	15	4	0
7.5	0	0	0	0	0	9	30	10	2	0
8	0	0	0	0	0	2	20	16	4	0
8.5	0	0	0	0	0	0	10	9	7	0
9	0	0	0	0	0	0	5	18	1	2
9.5	0	0	0	0	0	0	2	8	2	0
10	0	0	0	0	0	0	1	4	0	1
10.5	0	0	0	0	0	0	0	1	0	0
	4	5	6	7	8	9	10	11	12	13

Mean wave period (s)

Fig. 4. Scatter plot of the Belmullet wave energy test site.

Significant wave height (m)										
0.5	0	0	0	0	0	0	0	0	0	0
1	0	0	22	34	38	37	32	26	21	0
1.5	0	32	65	83	86	78	65	53	42	33
2	0	57	115	148	152	138	116	93	74	59
2.5	0	89	180	231	238	216	181	146	116	92
3	0	129	260	332	332	292	240	210	167	132
3.5	0	0	354	438	424	377	326	260	215	180
4	0	0	462	540	530	475	384	339	267	213
4.5	0	0	544	642	628	562	473	382	338	266
5	0	0	0	726	707	670	557	472	369	328
5.5	0	0	0	750	750	737	658	530	446	355
6	0	0	0	750	750	750	711	619	512	415
6.5	0	0	0	750	750	750	750	658	579	481
7	0	0	0	0	750	750	750	750	613	525
7.5	0	0	0	0	750	750	750	750	686	593
8	0	0	0	0	0	750	750	750	750	625
8.5	0	0	0	0	0	0	750	750	750	750
9	0	0	0	0	0	0	0	750	750	750
9.5	0	0	0	0	0	0	0	0	750	750
10	0	0	0	0	0	0	0	0	0	750
10.5	0	0	0	0	0	0	0	0	0	0
	4	5	6	7	8	9	10	11	12	13

Mean wave period (s)

Fig. 5. Power matrix of the Pelamis P1 device (kW).

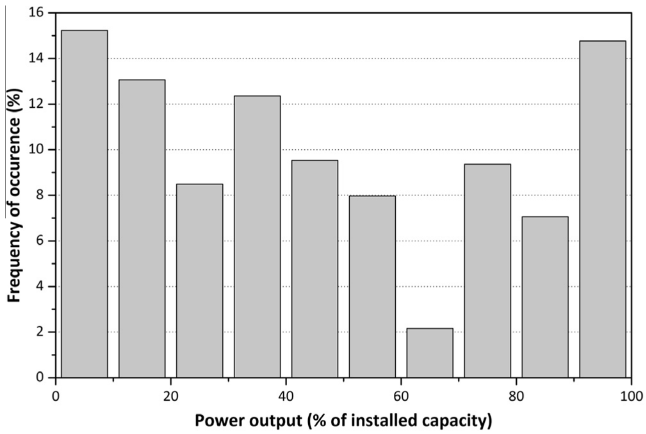

Fig. 6. Case study power output histogram.

6.2. Technical feasibility

As previously discussed, reactive power compensation allows maximum real power transfer through the cable and also ensures supply voltage quality in the offshore network. It influences the power flow in the transmission link and has an impact on the power loss in the system. Fig. 7 shows the size of onshore and offshore reactive power compensation required for the three voltage levels and the range of farm sizes and distances to the shore considered. Note that the instantaneous values of reactive power compensation required for a farm under different sea states and power generation levels are not the same as the reactive power compensator sizes shown in Fig. 7. These instantaneous values of reactive power compensation, obtained from the iterative procedure described earlier, have been used in the power flow runs that evaluate the losses in the transmission system.

For the 11 kV system, since the cable MVA ratings were greater than the farm size, there was found to be no requirement for any offshore compensation to free up the cable capacity. The offshore compensation requirement shown in Fig. 7(b) is purely to ensure that the voltage at bus 2 (Fig. 1) stayed within limits. This issue is significant for lower rated cables, which have higher resistances. The voltage rise issue meant that for some farm sizes and distances to the shore the real power generated by the farm had to be constrained to ensure continued connection to the onshore network. This would have severe financial implications on the developer and would be an unacceptable scenario in reality. In this case, uprated cables, with a lower resistance and higher MVA rating, would be used.

For both the 11 kV and the 33 kV transmission options, the charging current and hence the onshore reactive power compensation requirement increases with an increase in distance to the shore and with an increase in the farm size. The presence of any offshore reactive power compensation affects the amount of reactive power compensation required onshore, which explains any behaviour away from these two general trends. For the 33 kV option, a few cases where there is a requirement for offshore compensation are seen. This is again attributed to the relatively higher resistance of the lower rated cables, which causes voltage violations at bus 2 (Fig. 1).

For the 132 kV transmission case, no requirement for any offshore compensation was found. This is partly due to the fact that a 96.02 MVA cable is used for all farm sizes up till 90 MW, being the lowest rated cable at that voltage level. This allows the cable to carry the reactive power the cable generates, without having to constrain the real power output of the farm. This is an unlikely scenario but has been included for completeness. Additionally, owing to the lower resistance (when compared to the 11 kV and 33 kV options) and the higher operating voltage (causing smaller currents for the same power) no voltage violations at bus 2 (Fig. 1) were seen for any sea state and farm size. The two general trends reported in the 33 kV system, with respect to onshore compensation, are also observed for the 132 kV system.

6.3. Techno-economic assessment

6.3.1. Technical considerations

Fig. 8 shows the percentage energy lost over a year for the range of farm sizes and distances from the shore when an 11 kV, 33 kV and a 132 kV transmission link is used. The percentage is with respect to the total energy yield of the farm over the year in Watt-hours, obtained by multiplying the power matrix and the scatter plot and adding the energy generated over all the sea states.

For the three transmission voltages and the same farm size, the percentage energy lost increased with an increase in distance to the shore. This is as expected since the resistance of the cable increases proportionally to the cable length. An increase in the cable length also increases the reactive power generated by it, which in turn increases the cable current. This also contributes to the increase in the energy losses seen when the distance to the shore increases.

Distance from the shore (km)	0.75	1.5	3	4.5	6	7.5	9	10.5	12
10	0.09	0.09	1.14	0.25	0.52	0.80	1.10	1.43	1.91
15	0.13	0.13	1.99	1.85	0.54	0.87	1.25	1.67	2.26
20	0.18	0.71	2.26	2.53	2.11	0.93	1.39	1.90	2.60
25	0.22	1.31	2.45	2.94	2.86	2.17	1.83	2.11	2.93
30	0.27	1.60	2.43	3.14	3.30	2.89	2.64	2.31	3.26
35	0.32	1.79	2.53	3.25	3.54	3.27	3.20	2.51	3.60
40	0.37	1.88	2.52	3.23	3.80	3.55	3.58	2.70	3.94
45	0.43	1.98	2.51	3.36	3.96	3.89	3.96	3.01	4.31
50	0.49	1.95	3.56	3.36	3.97	4.08	4.25	3.34	4.71

Farm size (MW)

(a) onshore reactive power compensation for the 11 kV system

Distance from the shore (km)	0.75	1.5	3	4.5	6	7.5	9	10.5	12
10	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	1.90	1.60	0.00	0.00	0.00	0.00	0.00
20	0.00	0.80	2.20	2.30	1.50	0.00	0.00	0.00	0.00
25	0.00	1.40	2.40	2.70	2.20	1.10	0.30	0.00	0.00
30	0.00	1.70	2.40	2.90	2.60	1.70	0.90	0.00	0.00
35	0.30	1.90	2.50	3.00	2.80	2.00	1.30	0.00	0.00
40	0.60	2.00	2.50	3.00	3.00	2.20	1.50	0.00	0.00
45	0.80	2.10	2.50	3.10	3.10	2.40	1.70	0.10	0.00
50	0.90	2.10	3.00	3.10	3.10	2.50	1.80	0.30	0.00

Farm size (MW)

(b) offshore reactive power compensation for the 11 kV system

Distance from the shore (km)	4.5	9.75	15	19.5	24.75	30	34.5	39.75	45	48
10	0.48	0.48	0.72	1.56	2.20	3.23	3.01	4.12	5.39	5.27
15	0.72	0.72	0.87	1.39	2.05	3.17	3.04	4.22	5.59	5.58
20	0.97	0.97	1.17	1.30	1.89	3.09	3.04	4.30	5.77	5.87
25	1.21	1.21	1.46	1.63	1.97	2.99	3.03	4.37	5.94	6.16
30	1.45	1.45	1.76	1.96	2.37	2.88	3.00	4.41	6.11	6.43
35	1.70	1.70	2.05	2.29	2.77	3.13	3.36	4.44	6.27	6.7
40	1.93	3.59	2.34	2.62	3.16	3.57	3.85	4.46	6.42	6.96
45	2.18	4.68	2.64	2.94	3.56	4.02	4.33	4.95	6.56	7.21
50	2.43	5.12	2.94	3.27	3.96	4.48	4.82	5.51	6.70	7.46

Farm size (MW)

(c) onshore reactive power compensation for the 33 kV system

Distance from the shore (km)	4.5	9.75	15	19.5	24.75	30	34.5	39.75	45	48
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35	0.00	2.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40	0.00	4.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
45	0.00	5.80	1.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	0.00	6.50	3.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Farm size (MW)

(d) offshore reactive power compensation for the 33 kV system

Distance from the shore (km)	9.75	19.75	30	39.75	49.5	60	69.75	79.5	90	99.75
10	7.12	7.12	7.12	7.12	7.12	7.12	7.12	7.12	7.12	8.13
15	10.68	10.68	10.68	10.68	10.68	10.68	10.68	10.68	10.68	11.50
20	14.25	14.25	14.25	14.25	14.25	14.25	14.25	14.25	14.25	15.34
25	17.81	17.81	17.81	17.81	17.81	17.81	17.81	17.81	17.81	19.18
30	21.38	21.38	21.38	21.38	21.38	21.38	21.38	21.38	21.38	23.02
35	24.95	24.95	24.95	24.95	24.95	24.95	24.95	24.95	24.95	26.87
40	28.53	28.54	28.54	28.54	28.54	28.54	28.54	28.54	28.54	30.73
45	32.12	32.12	32.12	32.13	32.13	32.13	32.13	32.13	32.13	34.60
50	35.72	35.72	35.72	35.72	35.73	35.73	35.73	35.73	35.73	38.47

Farm size (MW)

(e) onshore reactive power compensation for the 132 kV system

Distance from the shore (km)	9.75	19.75	30	39.75	49.5	60	69.75	79.5	90	99.75
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Farm size (MW)

(f) offshore reactive power compensation for the 132 kV system

Fig. 7. Sizing of reactive power compensation given in MVAr for the considered system.

For the same distance to shore, the percentage energy lost increases initially and then decreases as the size of the farm increases. For example, for the 11 kV transmission system, considering the 50 km distance to shore case, the percentage energy lost peaks for the 3 MW farm and then drops. This can be attributed to the fact that energy lost is a function of the farm size and the resistance of the cable being used. The resistance of cables drops significantly as the cable rating increases, as shown in Fig. 9. The same cable (rated at 3.18 MVA) has been used for the first three farm sizes (0.75–3 MW) in the 11 kV case and hence the energy loss peaked for the highest farm size from amongst the three. A similar feature is seen for the 33 kV transmission system, wherein the same cable is used for the first two farm sizes (4.5–9.75 MW).

The 132 kV transmission case is slightly different from the 11 kV and 33 kV cases. This is because the smallest 132 kV cable has an MVA rating of 96.02 MVA. This meant that the same cable was used for all farm sizes up to 90 MW.

Considering the 132 kV system, for the same distance to shore, the percentage energy lost reduces initially and then increases with an increase in the farm size (up to the 90 MW farm). The power losses in the transmission cable are a function of both the real power and reactive power carried by it. For lightly loaded cables (up to 39.75 MW), the significantly higher reactive power the cable carries contributes more towards the losses. As the farm size increases from 9.75 MW to 39.75 MW, the cable loading increases, which reduces the reactive power generated by the cable and hence reduces the power transmission losses. For farm sizes greater than 39.75 MW up till 90 MW, the real power the cable carries contributes more towards the power losses. Therefore, with an increase in the farm size, the transmission loss increases. For the 99.75 MW farm, using a higher rated cable (109.74 MVA) with a smaller resistance when compared to the 96.02 MVA rated cable used so far (Fig. 9) produces lower losses for all the distances when compared to the 90 MW farm.

Distance from the shore (km) \ Farm size (MW)	0.75	1.5	3	4.5	6	7.5	9	10.5	12
10	2.53	4.18	7.65	5.79	4.68	3.93	3.63	2.77	2.56
15	3.48	5.84	12.73	8.58	6.56	5.53	5.12	3.92	3.61
20	4.46	8.06	20.30	12.19	8.68	7.02	6.53	5.03	4.63
25	5.49	12.41	28.24	16.36	11.09	8.67	7.90	6.10	5.63
30	6.60	17.92	35.68	20.80	13.64	10.42	9.37	7.14	6.62
35	7.81	24.14	43.55	25.27	16.29	12.18	10.87	8.15	7.59
40	9.77	30.01	51.06	29.73	19.04	14.00	12.42	9.13	8.56
45	12.50	36.20	58.25	34.36	21.60	15.95	13.97	10.14	9.53
50	15.29	41.87	64.65	38.64	24.30	17.77	15.57	11.20	10.51

(a) percentage energy lost for 11 kV transmission system

Distance from the shore (km) \ Farm size (MW)	0.75	1.5	3	4.5	6	7.5	9	10.5	12
10	1.00	1.00	1.03	1.05	1.09	1.14	1.21	1.35	1.46
15	1.07	1.07	1.10	1.15	1.18	1.26	1.36	1.56	1.72
20	1.14	1.15	1.17	1.24	1.30	1.38	1.50	1.77	1.98
25	1.21	1.23	1.24	1.32	1.40	1.51	1.66	1.98	2.24
30	1.28	1.30	1.31	1.40	1.50	1.63	1.81	2.19	2.50
35	1.35	1.37	1.38	1.48	1.59	1.75	1.96	2.39	2.77
40	1.42	1.44	1.45	1.56	1.69	1.87	2.10	2.60	3.03
45	1.49	1.51	1.52	1.64	1.79	1.99	2.25	2.82	3.29
50	1.56	1.58	1.59	1.71	1.88	2.10	2.40	3.03	3.55

(b) relative cost for 11 kV transmission system

Distance from the shore (km) \ Farm size (MW)	4.5	9.75	15	19.5	24.75	30	34.5	39.75	45	48
10	1.27	2.43	1.85	1.66	1.33	1.31	1.11	1.05	0.82	0.80
15	1.77	3.40	2.62	2.31	1.85	1.81	1.57	1.46	1.10	1.11
20	2.28	4.34	3.36	2.94	2.35	2.30	2.01	1.86	1.38	1.41
25	2.81	5.25	4.09	3.56	2.84	2.78	2.45	2.26	1.66	1.71
30	3.37	6.13	4.79	4.16	3.32	3.25	2.88	2.65	1.94	2.00
35	3.98	7.11	5.48	4.75	3.80	3.71	3.30	3.03	2.22	2.29
40	4.64	8.47	6.16	5.33	4.26	4.16	3.71	3.42	2.49	2.59
45	5.36	9.98	6.87	5.90	4.73	4.61	4.13	3.79	2.77	2.88
50	6.16	11.49	7.68	6.46	5.18	5.05	4.53	4.17	3.04	3.17

(c) percentage energy lost for 33 kV transmission system

Distance from the shore (km) \ Farm size (MW)	4.5	9.75	15	19.5	24.75	30	34.5	39.75	45	48
10	1.06	1.08	1.20	1.25	1.37	1.47	1.68	1.79	2.10	2.19
15	1.14	1.16	1.30	1.38	1.55	1.67	1.95	2.11	2.58	2.67
20	1.22	1.24	1.41	1.51	1.72	1.88	2.21	2.43	3.05	3.14
25	1.30	1.32	1.51	1.64	1.89	2.08	2.48	2.75	3.52	3.62
30	1.38	1.40	1.61	1.77	2.07	2.29	2.74	3.08	4.00	4.09
35	1.46	1.50	1.72	1.90	2.24	2.49	3.01	3.40	4.47	4.56
40	1.54	1.59	1.82	2.03	2.42	2.70	3.28	3.72	4.94	5.04
45	1.61	1.68	1.94	2.16	2.59	2.90	3.54	4.04	5.42	5.51
50	1.69	1.76	2.06	2.29	2.77	3.11	3.81	4.36	5.89	5.98

(d) relative cost for 33 kV transmission system

Distance from the shore (km) \ Farm size (MW)	9.75	19.75	30	39.75	49.5	60	69.75	79.5	90	99.75
10	0.44	0.40	0.42	0.38	0.38	0.46	0.53	0.55	0.59	0.53
15	0.50	0.46	0.48	0.45	0.48	0.57	0.66	0.70	0.75	0.66
20	0.60	0.53	0.56	0.54	0.58	0.69	0.79	0.84	0.91	0.80
25	0.75	0.63	0.65	0.64	0.69	0.81	0.92	0.99	1.08	0.94
30	0.98	0.76	0.76	0.76	0.81	0.94	1.06	1.15	1.24	1.08
35	1.29	0.94	0.90	0.89	0.95	1.09	1.21	1.31	1.42	1.23
40	1.70	1.16	1.08	1.05	1.10	1.24	1.38	1.48	1.60	1.38
45	2.22	1.44	1.28	1.23	1.28	1.42	1.55	1.66	1.79	1.54
50	2.88	1.78	1.53	1.45	1.48	1.61	1.74	1.86	2.00	1.71

(e) percentage energy lost for 132 kV transmission system

Distance from the shore (km) \ Farm size (MW)	9.75	19.75	30	39.75	49.5	60	69.75	79.5	90	99.75
10	1.38	1.44	1.50	1.59	1.69	1.69	1.75	1.81	1.87	2.06
15	1.59	1.65	1.71	1.80	1.89	1.89	1.96	2.02	2.08	2.34
20	1.80	1.86	1.92	2.01	2.10	2.10	2.17	2.23	2.29	2.61
25	2.00	2.07	2.13	2.22	2.31	2.31	2.37	2.44	2.50	2.89
30	2.21	2.28	2.34	2.43	2.52	2.52	2.58	2.65	2.71	3.16
35	2.42	2.48	2.55	2.64	2.73	2.73	2.79	2.85	2.92	3.44
40	2.63	2.69	2.76	2.85	2.94	2.94	3.00	3.06	3.13	3.71
45	2.84	2.90	2.96	3.06	3.15	3.15	3.21	3.27	3.33	3.99
50	3.05	3.11	3.17	3.27	3.36	3.36	3.42	3.48	3.54	4.26

(f) relative cost for 132 kV transmission system

Fig. 8. Techno-economic comparison of the considered systems.

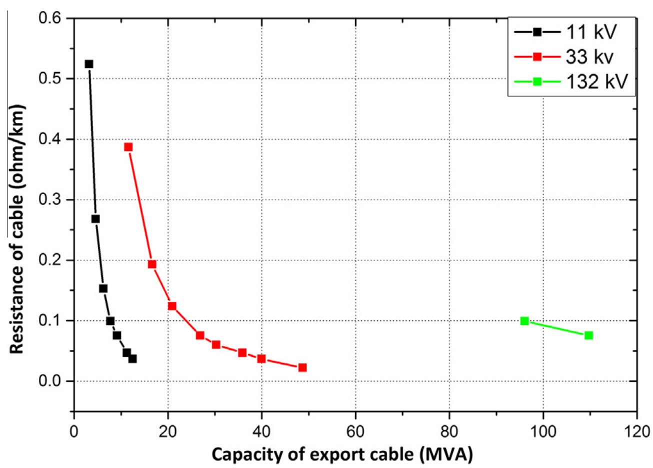

Fig. 9. Cable resistance for different cable MVA ratings.

6.3.2. Transmission system cost analysis

Since there are uncertainties with respect to the cost of the different equipment and because some of these costs may be project-specific, only relative costs of the different cases with respect to a base case will be discussed in this paper. Fig. 8 shows the relative costs of the system which have been normalised against the base case of a 0.75 MW farm 10 km from the shore using an 11 kV transmission voltage. Note that the same colour map has been used in Fig. 8(b), (d) and (f) that compare the relative costs.

The analysis of the transmission system costs reveals several interesting points for discussion. As expected, the cost of the transmission system will generally increase with both rated voltage and power. However, the results in Fig. 8 reveal that this rule is not always true. For systems around 40–50 MW installed capacity, 33 kV and 132 kV transmission systems are technically feasible. However, although 33 kV equipment is generally cheaper than equipment rated for 132 kV, the relative cost for this range of farm sizes is higher for the 33 kV system. This can be attributed to the fact that the cable costs contributes significantly to the total cost and that the 30–50 MVA cable at 33 kV costs more than the 132 kV cable rated at 90 MVA.

For the three transmission voltages considered, the cost of the substation platform and the subsea cable contributed between 94% and 98% (11 kV system), 88% and 97% (33 kV system) and 78% and 94% (132 kV system) of the total cost of the transmission system infrastructure. The costs of other equipment, like the switchgear, reactive power compensation and transformers, increases with an increase in their MVA and voltage ratings. This explains why the contribution of cables and platform to the total cost reduces as the voltage level and farm size, and hence equipment MVA ratings, increase.

The subsea cable link contributes the most to the total transmission system infrastructure cost for larger MEC farms further offshore. For smaller farms closer to the shore, the platform cost was found to be significantly higher than the cable costs. Therefore, there is potential to reduce the cost of the first commercial scale MEC arrays by investing in cost reduction of offshore platforms/substations. As discussed in Section 2, there are several options currently being developed for use in the MRE sector. By moving away from surface piercing platforms, which require large and expensive foundations, there is potential to reduce this cost.

6.3.3. Impact of component uprating on system cost

This section presents an example of how introducing spare capacity into the system can help to lower the relative cost, illustrating how the increase in the supply cost can be offset by a reduction in the transmission losses. Fig. 10 shows the cost associated with the losses, the cost of the transmission system investment and the total cost for a 9.75 MW farm 15 km from the shore using a 33 kV transmission voltage, for a range of network capacities (11.54–48.69 MVA). Note that network capacity includes the capacity of the offshore substation transformer and the transmission cable to the shore with the rating of the offshore substation transformer selected to be equal to or higher than the rating of the selected cable. The costs in the figure are normalised with respect to the cost of an 11 kV transmission link used for a 0.75 MW farm 10 km from the shore. The costs associated with losses have been obtained over the 25-year period of operation of the farm, assuming that the energy losses on average, over every year, remain equal. The strike price set in the UK for wave energy (of £305/MWh) under the new Contracts for Difference regime [16] was used to calculate the loss of revenue due to energy losses in the transmission system.

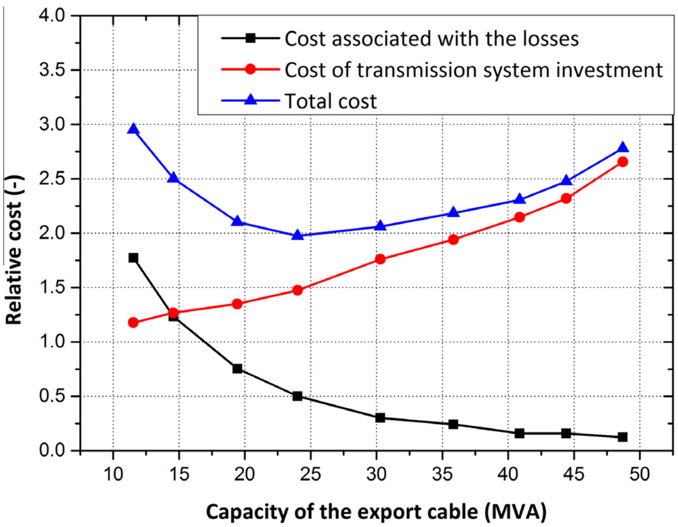

Fig. 10. Different transmission system costs for the 9.75 MW farm 15 km from the shore using a 33 kV transmission voltage.

The results in Fig. 10 show that the cost of the transmission system investment increases with an increase in network capacity. However, the cost associated with the transmission losses display a nonlinear trend which is a direct consequence of the impedance characteristics. Fig. 9 showed the drop in the cable resistance with increased capacity of cables. This drop in resistance leads to lower losses for the same farm size, when the cable capacity increases. This can be seen in Fig. 10 with the costs associated with losses reducing with increased capacity of the network. From the total cost curve in the figure, it can be concluded that for the 9.75 MW farm, 15 km from the shore using a 33 kV transmission voltage, a 24 MVA transmission cable and a 25 MVA offshore substation transformer is the cheapest transmission system option. In comparison with the system wherein the cable and transformer ratings are chosen purely based on the size of the farm, this provides a cost saving of approximately 50%.

7. Conclusions

A comprehensive assessment of electrical network options is a vital part of developing commercial scale MEC farms. The work presented in this paper contributes to the research area by presenting a techno-economic analysis framework for selecting the optimum transmission system for a generic MEC farm. The approach is illustrated using a wave generation example to demonstrate the impact of technical feasibility and performance on the overall cost of the system.

Although, currently, the array cost is dominated by the cost of the MECs, as the sector matures the cost of the transmission system relative to the entire array will increase. Therefore, any cost savings in this area may have a considerable contribution towards the overall objective of improving the LCOE. The presented information will be useful for MEC farm developers to support decisions on the optimal transmission system configuration for their farm.

Future research will extend the model presented in this paper to include operation and maintenance (O&M) costs within the analysis. Including an appreciation of the O&M cost will improve the techno-economic framework and allow for a detailed analysis of the impact of reliability indices on the transmission network design. The presented methodology can also be extended to include the intra-array network design within the techno-economic analysis in order to quantify the impact of different array layouts on the relative cost of the overall electrical system. Applying this framework to a larger number of case studies will help to characterise performance based on the input parameters (farm rated power and distance to shore) and to standardise design decisions.

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Appendix A.

Table A.1. Cable electrical parameters.

Voltage (kV)	Capacity (MVA)	Resistance (Ω/km)	Inductance (mH/km)	Capacitance (μF/km)
11.00	3.1817	0.5240	0.4300	0.2300
11.00	4.5915	0.2680	0.3800	0.2900
11.00	6.2300	0.1530	0.3500	0.3500
11.00	7.7161	0.0991	0.3300	0.4200
11.00	9.1450	0.0754	0.3300	0.4800
11.00	11.2407	0.0470	0.3100	0.5900
11.00	12.4791	0.0366	0.3000	0.6600
33.00	11.5455	0.3870	0.4800	0.1400
33.00	16.6324	0.1930	0.4200	0.1700
33.00	20.9191	0.1240	0.3900	0.1900
33.00	26.8633	0.0754	0.3600	0.2300
33.00	30.2927	0.0601	0.3600	0.2600
33.00	35.8368	0.0470	0.3400	0.2800
33.00	39.9520	0.0366	0.3200	0.3200
132.00	96.0221	0.0991	0.4700	0.1300
132.00	109.7395	0.0754	0.4400	0.1400

Table A.2. Transformer electrical parameters (per-unit to a 100 MVA base).

Voltage (kV)	Capacity (MVA)	Resistance (pu)	Inductance (pu)
11.00	0.80	1.2087	5.8132
11.00	1.60	0.4738	3.0889
11.00	3.15	0.2218	2.2111
11.00	6.30	0.0915	1.1870
11.00	8.00	0.0732	1.0600
11.00	10.00	0.0561	0.8982
11.00	12.50	0.0453	0.7987
33.00	6.30	0.0976	1.2661
33.00	10.00	0.0561	0.8982
33.00	20.00	0.0233	0.4995
33.00	25.00	0.0170	0.3996
33.00	30.00	0.0145	0.3664
33.00	45.00	0.0083	0.2443
33.00	60.00	0.0061	0.1999
132.00	10.00	0.0624	0.9981
132.00	20.00	0.0256	0.5494
132.00	30.00	0.0158	0.3997
132.00	45.00	0.0090	0.2665
132.00	60.00	0.0064	0.2082
132.00	70.00	0.0062	0.2142
132.00	80.00	0.0052	0.1874
132.00	90.00	0.0045	0.1666
132.00	100.00	0.0039	0.1499

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